LA-UR- 02-4467

c.1

Approved for public release; distribution is unlimited.

Title. BOSON-FERMION MIXTURES IN TWO-COLOR OPTICAL DIPOLE TRAPS

Author(s) R. Onofrio and C. Presilla

Submitted to. ICAP 2002, Eigthteenth International Conference on Atomic Physics

Los Alamos NATIONAL LABORATORY

Reaching Fermi degeneracy in two-species optical dipole traps

Roberto Onofrio[1,2,3] and Carlo Presilla[2,4,5]

[1]Dipartimento di Fisica "G. Galilei", Università di Padova, Italy
[2]INFM Unit%di Roma 1 and Center for Statistical Mechanics and Complexity
[3]Los Alamos National Laboratory, Los Alamos, New Mexico
[4]Dipartimento di Fisica, Università di Roma "La Sapienza", Italy
[5]INFN Sezione di Roma 1

abstract

We propose the use of a combined optical dipole trap to achieve Fermi degeneracy by sympathetic cooling with a different bosonic species. Two far-detuned pairs of laser beams focused on the atomic clouds are used to confine the two atomic species with different trapping strengths. We show that a deep Fermi degeneracy regime can be potentially achieved earlier than Bose-Einstein condensation, as discussed in the favorable situation of a ^{6}Li–^{23}Na mixture. This opens up the possibility of experimentally investigating a mixture of superfluid Fermi and normal Bose gases.

Lack of efficient cooling techniques for fermions

One limitation of current efforts to reach Fermi degeneracy arises from the use of magnetic trapping techniques, where spin-polarized Fermi gases are obtained. The Pauli principle limits the efficiency of direct evaporative cooling among fermions in the same hyperfine state, and also inhibits scattering among fermions in different hyperfine states (Pauli blocking).

An alternative technique, the sympathetic cooling of fermions through coupling to an ultracold bosonic reservoir, is limited by the decreased efficiency of the elastic scattering between fermions and bosons expected when the latter enter a superfluid regime, and ultimately by Pauli blocking.

Optical dipole traps

More flexible trapping tools are offered by optical dipole traps. These allow both trapping of different hyperfine states and the application of an arbitrary magnetic field.

A further advantage of using an optical dipole trap is the possibility of trapping different species with selective confinement strengths.

We discuss the case of an optical dipole trap obtained with the combination of two laser beams resulting in different trapping potentials for the two species of a mixture of Bose and Fermi gases. The trapping potentials can be engineered to make the Fermi gas more strongly confined than the Bose gas and, therefore, the Fermi temperature higher than the BEC critical temperature

Fermi and BEC critical temperatures

For a system of N_f Fermions trapped in a harmonic potential

$$T_\mathrm{F} = 6^{1/3}\ \hbar\omega_\mathrm{f}\ N_\mathrm{f}^{\frac{1}{3}} k_\mathrm{B}^{-1} = 1.82\ \hbar\omega_\mathrm{f}\ N_\mathrm{f}^{\frac{1}{3}} k_\mathrm{B}^{-1}$$

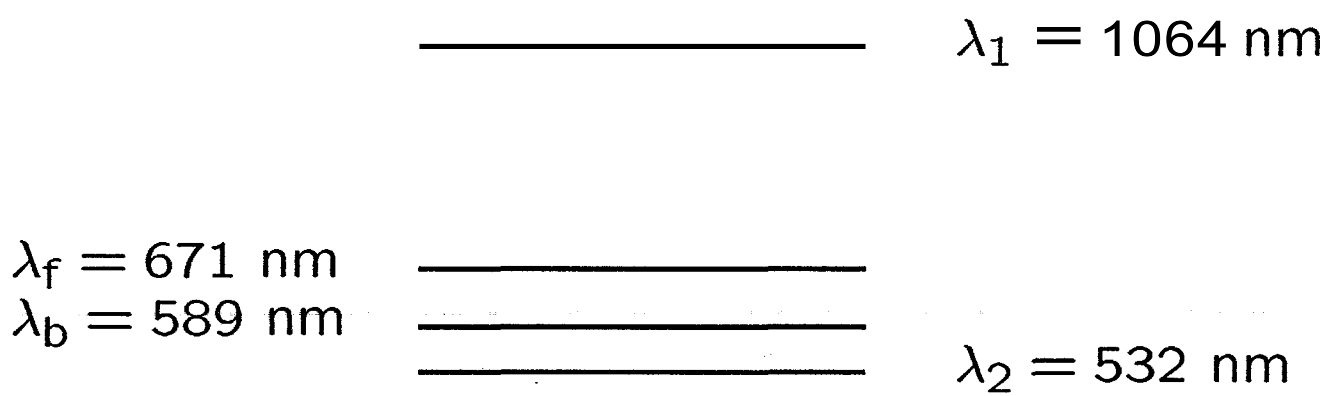
with $\omega_\mathrm{f} = (\omega_{\mathrm{f}x}\omega_{\mathrm{f}y}\omega_{\mathrm{f}z})^{1/3}$

For a system of N_b Bosons trapped in a harmonic potential

$$T_\mathrm{C} = \zeta(3)^{-1/3}\ \hbar\omega_\mathrm{b}\ N_\mathrm{b}^{\frac{1}{3}} k_\mathrm{B}^{-1} = 0.94\ \hbar\omega_\mathrm{b}\ N_\mathrm{b}^{\frac{1}{3}} k_\mathrm{B}^{-1}$$

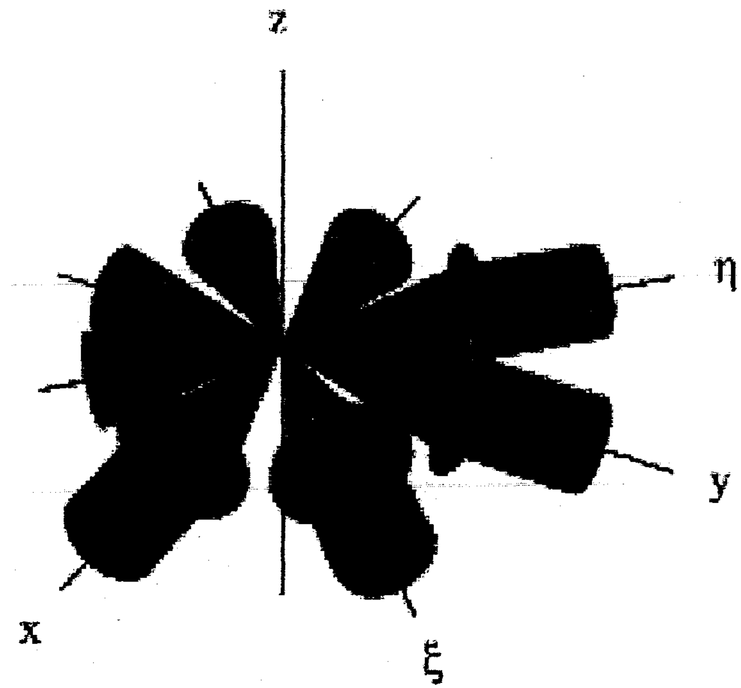
with $\omega_\mathrm{b} = (\omega_{\mathrm{b}x}\omega_{\mathrm{b}y}\omega_{\mathrm{b}z})^{1/3}$

Relevant atomic and laser wavelengths



Relevant atomic wavelengths for the D_2 lines in the case of a ^{6}Li-^{23}Na mixture and laser wavelengths for the optical trapping.

Laser trap geometry



Schematic of the geometry of the two pairs of red- and blue-detuned laser beams propagating along the orthogonal axes x-y and ξ-η, rotated by an angle $\theta = \pi/4$.

Laser trap potential

The effective potential energy felt by an atom of species a ($\alpha =$ b for ^{23}Na and $\alpha =$ f for ^{6}Li) and due to the laser beams i ($i = 1, 2$) is

$$U_i^\alpha(x,y,z) = -\frac{\hbar\Gamma_\alpha^2}{8I_\alpha^{\mathrm{sat}}}\left(\frac{1}{\Omega_\alpha - \Omega_i} + \frac{1}{\Omega_\alpha + \Omega_i}\right) I_i(x,y,z)$$

where Γ_α is the atomic transition line-width, $\Omega_\alpha = 2\pi c/\lambda_\alpha$, $\Omega_i = 2\pi c/\lambda_i$, I_i is the laser intensity, and I_α^{sat} is the saturation intensity for the atomic transition, expressed in terms of the former quantities as

$$I_\alpha^{\mathrm{sat}} = \hbar\Omega_\alpha^3\Gamma_\alpha/6c^2$$

Each laser intensity I_i is the incoherent sum of the intensities of the two beams propagating along the orthogonal directions

$$\xi = x\cos\theta + y\sin\theta \qquad \eta = y\cos\theta - x\sin\theta$$

We choose $\theta = 0$ for the red-detuned beams and $0 \leq \theta \leq \pi/4$ for the blue-detuned ones

$$I_i(x,y,z) = \frac{2P_i\, e^{-\frac{2(\eta^2+z^2)}{w_i^2\left(1+\frac{\xi^2}{R_i^2}\right)}}}{\pi w_i^2\left(1+\frac{\xi^2}{R_i^2}\right)} + \frac{2P_i\, e^{-\frac{2(\xi^2+z^2)}{w_i^2\left(1+\frac{\eta^2}{R_i^2}\right)}}}{\pi w_i^2\left(1+\frac{\eta^2}{R_i^2}\right)}$$

where P_i is the beam power, w_i is the $1/e^2$ beam waist radius, and $R_i = \pi w_i^2/\lambda_i$ is the Rayleigh range.

Relevant data for ^{6}Li–^{23}Na mixtures trapped with Nd:YAG lasers

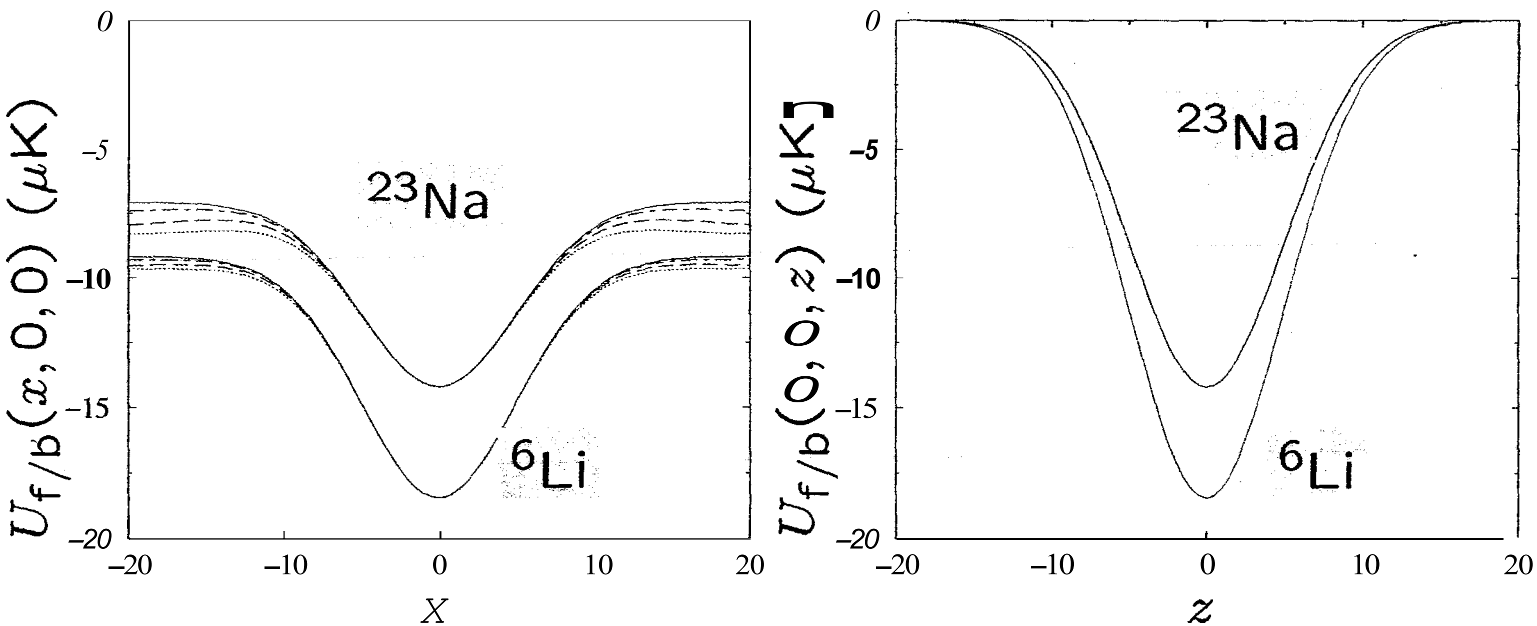
^{6}Li	$\lambda_f = 671$ nm	$\Gamma_f = 5.9$ MHz	$m_f = 9.6 \times 10^{-27}$ Kg
^{23}Na	$\lambda_b = 589$ nm	$\Gamma_b = 9.8$ MHz	$m_b = 36.8 \times 10^{-27}$ Kg

red-detuned laser	$\lambda_1 = 1064$ nm	$w_1 = 10\ \mu$m
blue-detuned laser	$\lambda_2 = 532$ nm	$w_2 = 10\ \mu$m

$\Omega_f = 2\pi c/\lambda_f = 2.81 \times 10^{15}$ s^{-1} $\Omega_b = 2\pi c/\lambda_f = 3.20 \times 10^{15}$ s^{-1}

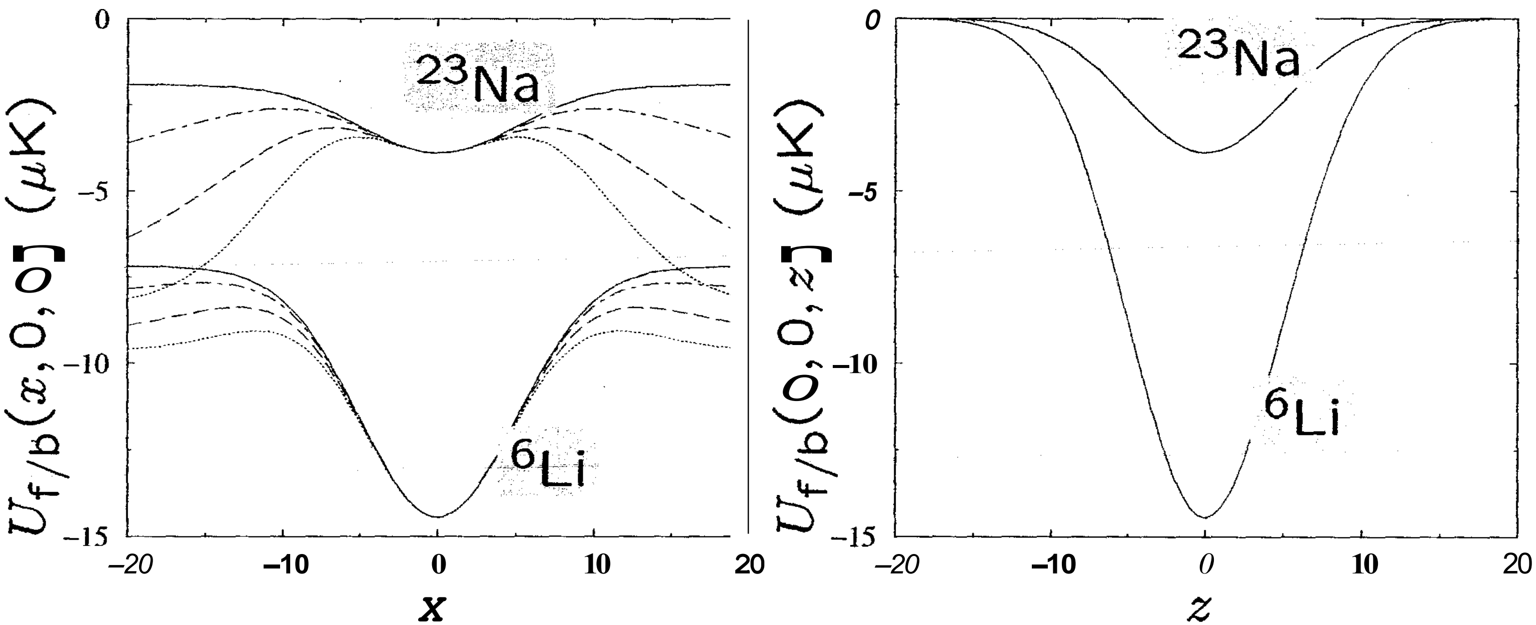
$\Omega_1 = 2\pi c/\lambda_f = 1.77$ x 10^{15} s^{-1} $\Omega_2 = 2\pi c/\lambda_f = 3.54$ x 10^{15} s^{-1}

Trap potentials U_f and U_b at $P_2/P_1 = 0.05$



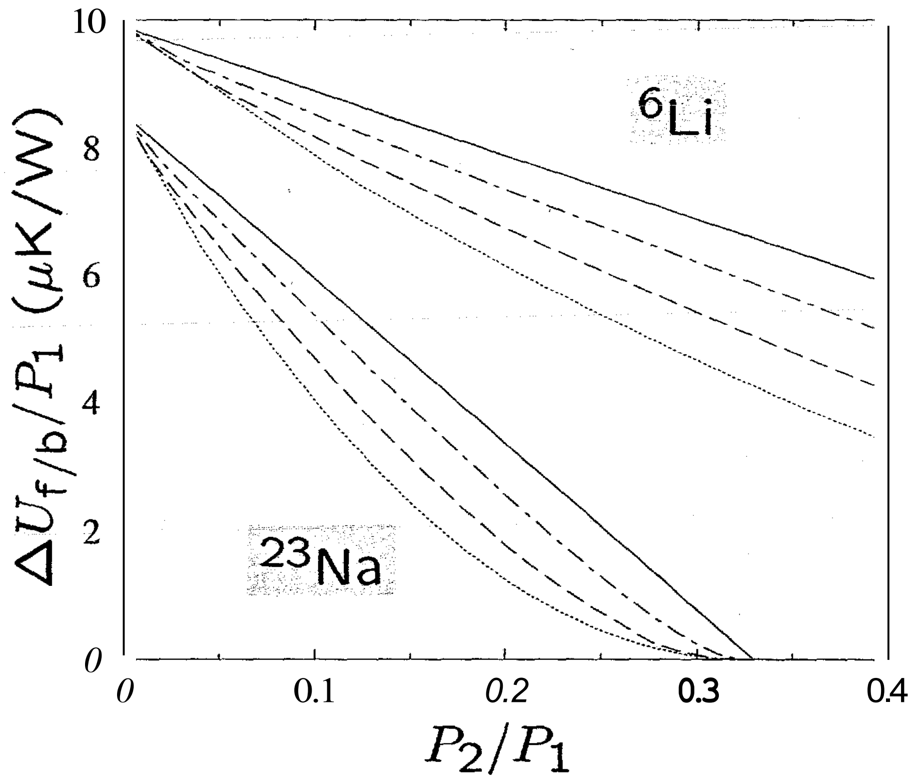
From top to bottom curves obtained with blue-detuned beams rotated with respect to red-ones by $\theta = 0$, $\pi/16$, $\pi/8$, **and** $\pi/4$, respectively.

Trap potentials U_f and U_b at $P_2/P_1 = 0.25$



From top to bottom curves obtained with blue-detuned beams rotated with respect to red-ones by $\theta = 0$, $\pi/16$, $\pi/8$, and $\pi/4$, respectively.

Confining energies ΔU_{f} and ΔU_{b} *vs* beam power ratio



From top to bottom curves obtained with blue-detuned beams rotated with respect to red-ones by $\theta = 0$, $\pi/16$, $\pi/8$, and $\pi/4$, respectively.

Small oscillation frequencies at the trap minimum

The potentials experienced by fermions and bosons

$$U_{\mathrm{f}} = U_1^{\mathrm{f}} + U_2^{\mathrm{f}} \qquad U_{\mathrm{b}} = U_1^{\mathrm{b}} + U_2^{\mathrm{b}}$$

present, for P_2/P_1 not too large, a minimum at $(x, y, z) = (0, 0, 0)$. Neglecting the terms $(\lambda_i/\pi w_i)^2 \ll 1$, the small oscillation frequencies around this minimum are

$$\omega_{\alpha x} = \omega_{\alpha y} = \frac{\omega_{\alpha z}}{\sqrt{2}} = \sqrt{\frac{\hbar}{2\pi m_\alpha}\left(\frac{k_1^\alpha P_1}{w_1^4} + \frac{k_2^\alpha P_2}{w_2^4}\right)},$$

where m_α is the mass of an atom of the species α and

$$k_i^\alpha = \frac{\Gamma_\alpha^2}{I_\alpha^{\mathrm{sat}}}\left(\frac{1}{\Omega_\alpha - \Omega_i} + \frac{1}{\Omega_\alpha + \Omega_i}\right)$$

Critical power ratio corresponding to unconfined bosons

Fermi and the BEC critical temperatures are determined by the average angular trapping frequencies

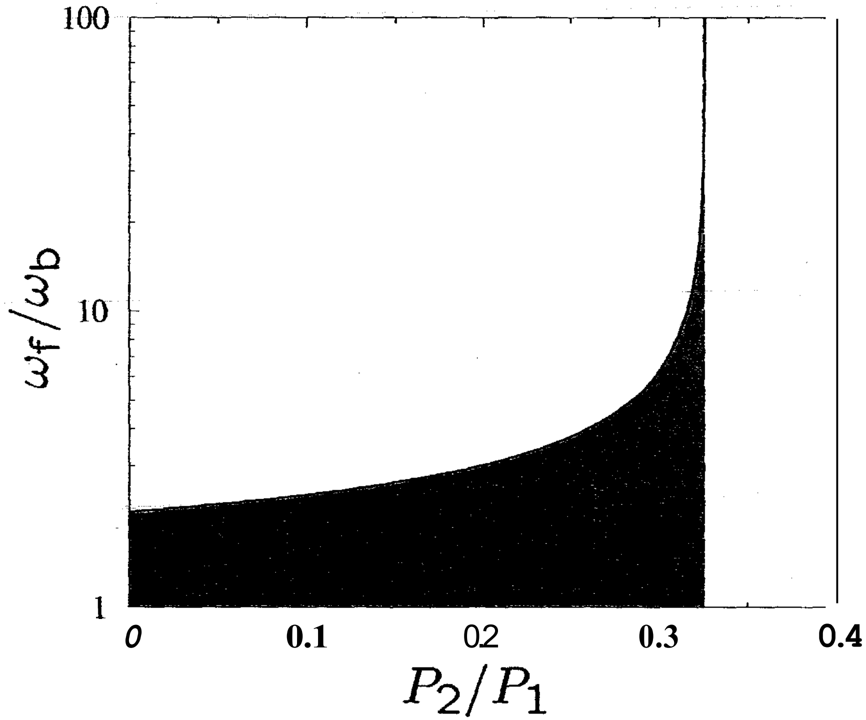
$$\omega_{\mathrm{f}} = (\omega_{\mathrm{f}x}\omega_{\mathrm{f}y}\omega_{\mathrm{f}z})^{1/3} \qquad \omega_{\mathrm{b}} = (\omega_{\mathrm{b}x}\omega_{\mathrm{b}y}\omega_{\mathrm{b}z})^{1/3}$$

The boson frequency vanishes, $\omega_{\mathrm{b}} = 0$, when the beam power ratio assumes the critical value

$$\left.\frac{P_2}{P_1}\right|_{\mathrm{crit}} = \frac{\Omega_2^2 - \Omega_{\mathrm{b}}^2}{\Omega_{\mathrm{b}}^2 - \Omega_1^2}\left(\frac{w_2}{w_1}\right)^4$$

For the system considered here $\left.\frac{P_2}{P_1}\right|_{\mathrm{crit}} \simeq 0.326$

Average angular trapping frequencies *vs* beam power ratio



$$\omega_\mathrm{f} = (\omega_{\mathrm{f}x}\omega_{\mathrm{f}y}\omega_{\mathrm{f}z})^{1/3}$$

$$\omega_\mathrm{b} = (\omega_{\mathrm{b}x}\omega_{\mathrm{b}y}\omega_{\mathrm{b}z})^{1/3}$$

Dashed line indicates the analytical prediction for the critical power ratio corresponding to unconfined bosons

Evaporative cooling dynamics

First, only the red-detuned laser is on and its power P_1 is decreased as typically done in an optical dipole trap.

When the temperature is approaching T_F, the blue-detuned laser is turned on with the ratio P_2/P_1 kept constant during the following stage of evaporation.

There is a trade-off in choosing the final ratio P_2/P_1 since the shallower confinement *of* the bosons also results in a smaller peak density of this species, hence a smaller elastic scattering rate, affecting both evaporative cooling and the subsequent sympathetic cooling of the fermions.

For $P_2/P_1 \simeq 0.31$ and $N_f = N_b$ we estimate $T \simeq 5 \times 10^{-2} T_F$ before the bosons condense.

Conclusions

We have outlined a novel strategy to reach a deep Fermi degenerate regime based upon a proper engineering *of* a two-species optical dipole trap.

The case of a ^{6}Li–^{23}Na mixture has been discussed in detail also due to the very favorable properties of this mixture recently reported in literature.

The strategy can be also applied to other mixtures such as ^{40}K–^{87}Rb or ^{6}Li–^{87}Rb for which $\lambda_b > \lambda_f$, by choosing a blue-detuned beam wavelength such that $\lambda_f < \lambda_2 < \lambda_b$.

Similar results can be obtained also by using a single optical dipole trap configuration.

Our proposal could pave the road to the experimental study of a novel phase consisting of a superfluid Fermi gas and a normal Bose gas, a situation precluded in the ^{3}He–^{4}He Fermi-Bose mixtures.

Besides providing access to a new system interesting in itself, this could considerably simplify signatures for fermion superfluidity based on the direct imaging of the density profile of the trapped fermions.